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Two-Way Time Transfer Via Communication Satellites

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Invited Paper

Some information on the history of two-way satellite time transfer is provided and developments in satellite communications technology conducive to this time transfer technique are mentioned. The difference between one-way and two-way satellite time transfer is explained, the advantages and disadvantages of the two-way method are pointed out, and the theory of the two-way technique using geostationary communication satellites is presented in detail showing the high accuracy potential of the method. The advantages of the use of spread spectrum techniques are outlined and the implementation of the two-way method using communication satellites and small earth stations employing pseudonoise (PN)-modems is described, and methods for signal delay calibration are dealt with. Existing links are listed and their performances are given. The precisions achieved are in the subnanosecond range and one expects accuracies of at least one nanosecond using small transportable stations for delay calibration. Finally, facts are summarized and the future use of the two-way technique employing communication satellites is discussed.

I. Introduction

A multitude of applications require time comparisons with high precision and accuracy over large distances [1]–[3]. These two requirements are incompatible for ground based radio-techniques. Very low frequencies (VLF) and low frequencies (LF) which would provide wide coverage are hampered by wave propagation phenomena in the Earth's atmosphere and limited bandwidth and therefore do not allow time comparisons with high precision and accuracy. On the other hand, large bandwidth and stable propagation are provided by very high frequencies (VHF) and higher frequencies, but only for line-of-sight connections. This contradiction could be resolved by the development of satellite methods which provide the use of high frequencies, the resulting large bandwidth, and wide coverage [4], [5]. Thus the progress of high precise and accurate time transfer over large distances is closely related to the development of satellite communications technology, a topic covered in [6]-[8]. A milestone in the development was the use of active relay satellites in the geostationary orbit (approximately 35 800 km above the equator) allowing worldwide communications by means of only three satellites spaced 120° apart.

The first time comparison experiment by means of a satellite was carried out as early as 1962 between the United States and the United Kingdom using the low orbiting communication satellite Telstar I [9]. The accuracy obtained was 1 μs for the satellite link only and 20 μs for the total link including the terrestrial links from the earth stations to the timekeeping institutions. This first attempt was followed by an ever increasing number of satellite time transfer experiments with the ultimate aim of developing inexpensive, reliable, and operational systems offering a high degree of availability [5], [10]–[12]. In the course of time the costs for satellite methods decreased continuously caused by the rapid growth of the satellite market and the development of satellite technology [13]–[16]. This concerns the development of low-priced low-noise preamplifiers (LNA's), low-noise converters (LNC's), and solid-state power amplifiers (SSPA's) and reliable high power traveling wave tube amplifiers (TWTA's) for spacecraft and as a hitherto last step the mass production of small earth stations so-called very small aperture terminals (VSAT's) for business communications and direct broadcast satellites. The use of VSAT's was made possible by employing higher frequencies (Ku-band rather than C-band) and more directional satellite antennas (spot beams) providing higher fluxes. Moreover, modulation schemes known as spread spectrum [17], [18]—mainly used at the beginning in military communication systems—have been employed. They make use of signal detection by correlation techniques and can therefore safely operate with very low signal levels and poor signal-to-noise ratios and in general allow the simultaneous use of the same frequency band of a satellite transponder without interference and are best suited for timing measurements of high precision and accuracy. Owing to these achievements only small earth stations are

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needed to make use of satellites for time transfer purposes and it is now feasible for time keeping institutions to set up dedicated low-cost on-site earth stations with receive-and-transmit capability. This collocation of time keeping stations and satellite earth stations is an important issue for the accuracy and availability of satellite time transfer links [19].

Basically one can distinguish between two different time transfer methods depending on the operating mode of the earth station: the one-way technique and the two-way technique [4], [5], [10]. In the one-way mode of operation a user simply receives signals which originate from a ground station and are rebroadcast by a satellite or signals which originate from a satellite with an on-board clock. For examples see [20] and [21]. In both cases the user merely needs a receive-only station and any number of users can be served. In the two-way technique, the users involved in a time transfer have to exchange timing signals via satellite and therefore require receive-and-transmit stations; in general this means more expensive equipment and more elaborate operational procedures than with the one-way method. Moreover, because the two-way mode is a point-to-point technique, the users have to work in pairs and need to exchange their measurement data. The main advantage of the two-way technique is that in contrast to the one-way method the knowledge of the satellite and user positions—necessary in order to calculate the signal delay along the path in the one-way method—is not the limiting factor for the obtainable accuracy, because for reciprocal paths between the stations the path delays cancel out and have therefore not to be calculated. Because of this fact, the two-way method has the potential to be the most accurate time transfer method and hence there exists a growing interest in the application of this technique and in its use on an operational basis. Starting with the Telstar experiment, which already employed the two-way technique, during the past years several experiments using this technique have been carried out [10]–[12], [22]. For the first time two-way experiments via geostationary satellites employing spread spectrum techniques and small on-site earth stations were carried out using the satellite Applications Technology Satellite (ATS)-1 [23], [24]. Accuracies and precisions of the order of 10 ns and 1 ns, respectively, were obtained. The highest precisions could be achieved recently using communication satellites with the MITREX-modem, which was the first commercial available spread spectrum modem especially designed for range measurements and point-to-point time transfer of highest precision and accuracy using geostationary satellites [25]–[32]. Since 1988, two-way time transfers, using domestic communication satellites, have been carried out between the U.S. Naval Observatory (USNO), Washington, DC, and the National Institute of Standards and Technology (NIST), Boulder, CO on a regular basis with precisions of some 100 ps and an expected accuracy of at least 1 ns after having calibrated the station delays [33], [34]. For the future, international and intercontinental links of this type are planned in accordance with a declaration and recommendations of the Comité Consultatif pour la Définition de la Seconde (CCDS) and a resolution of the Conférence Générale des Poids et Mesures (CGPM) concerning the "Implementation of two-way satellite links for international time comparisons for very high accuracy" [35]–[37].

II. Theory

The basic measurement setup in general use for two-way time transfers via communication satellites is illustrated in Fig. 1.

By means of the modem the one pulse per second (1 pps) is modulated onto the station's intermediate frequency (IF), which is usually at 70 MHz. The signal is then up-converted to the radio frequency (RF), amplified, and transmitted to the satellite. In the satellite transponder it is amplified, offset in frequency by the so-called satellite translation frequency and then amplified and retransmitted. At the receiving site the RF signal is again amplified, down-converted to the IF, and demodulated by means of the modem.

The measurement consists of simultaneous time interval measurements at both sites in which the local 1 pps starts both the local time interval counter and, transmitted via the satellite, stops the remote time interval counter. The time difference $T_1 - T_2$ between the clocks of stations 1 and 2 is given by the following equation:

$$\begin{aligned} T_1 - T_2 = {} & \frac{1}{2}(\Delta T_1 - \Delta T_2) \\ & + \frac{1}{2}\left[\left(\tau_1^U + \tau_2^D\right) - \left(\tau_2^U + \tau_1^D\right)\right] \\ & + \frac{1}{2}(\tau_{12} - \tau_{21}) \\ & + \Delta\tau_R \\ & + \frac{1}{2}\left[\left(\tau_1^{TX} - \tau_1^{RX}\right) - \left(\tau_2^{TX} - \tau_2^{RX}\right)\right]. \quad (1) \end{aligned}$$

In this equation the signal delays in the cables which connect the modems to the clocks and counters are ignored because they can easily be measured and accounted for.

The terms at the right hand side of (1) are selectively grouped according to their different nature and will be discussed in the following.

The first term $\frac{1}{2}(\Delta T_1 - \Delta T_2)$ is given by the difference of the respective counter readings of stations 1 and 2 which have to be exchanged in order to compute the clock differences.

The second term $\frac{1}{2}[(\tau_1^U + \tau_2^D) - (\tau_2^U + \tau_1^D)]$ contains the difference of the sums of the signal delays in the up links and down links for both signal directions (path delays). Under the assumption of path reciprocity this term would be zero, but because the signals penetrate the Earth's atmosphere the validity of this assumption has to be discussed in detail. Provided that the signals arrive at the satellite within a few milliseconds, the effect of satellite motion (some meters per second for a geostationary satellite) can be neglected, but nonreciprocity caused by the different up link and down link frequencies used has to be considered. For the ionosphere the excess delay for frequencies as high as employed in satellite communica-

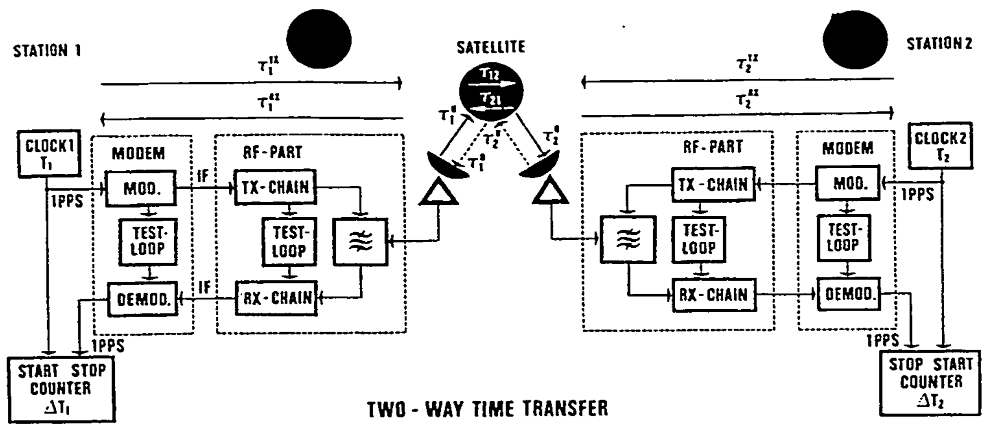

Fig. 1. Basic two-way measurement setup showing the different signal delays.

tions is proportional to the total electron content integrated along the signal path and to the reciprocal value of the signal frequency squared [38]. For Ku-band up link and down link frequencies of approximately 14 GHz and 12 GHz, respectively, the differential delays caused by the ionosphere can be neglected, but not for C-band (6/4 GHz) and certainly not for VHF frequencies [39]. The nonreciprocity due to the troposphere can be neglected for frequencies used for satellite communications but has to be considered at higher frequencies and especially at optical wavelengths where this effect is significant [38]–[40].

The third term $\frac{1}{2}(\tau_{12} - \tau_{21})$ consists of the signal delays of the satellite transponder for the signal directions from station 1 to station 2 and vice versa. When the same frequency band of one transponder is used for both signal directions, which is made possible by the use of spread spectrum techniques, then both delays are equal and the difference is zero. In the case of using different transponders for both signal directions, the delay difference has to be known.

The fourth term $\Delta\tau_R$ is a correction for the path nonreciprocity caused by the rotating Earth, known as Sagnac effect [24], [41]–[43]. It can be computed from the positions of the earth stations and the satellite and has small variations due to the movement of the satellite. This term can amount to some 100 ns, but can be calculated with sufficient accuracy for nanosecond time transfers without requiring high accuracy knowledge of the satellite's and earth stations' positions. The position accuracy requirements are several orders of magnitude below those for one-way methods. From this it is evident that the two-way method is superior to the one-way method if highest precision and accuracy is required.

The last term $\frac{1}{2}[(\tau_1^{TX} - \tau_1^{RX}) - (\tau_2^{TX} - \tau_2^{RX})]$ is given by the difference of the differential delays of the transmit and receive parts (equipment delays) of earth stations 1 and 2. These delays have to be measured individually or to be calibrated by means of some kind of transfer standard [29]–[31], [44], [45].

Considering the facts on the two-way method given above the general principle of the use of a transportable calibration station as transfer standard for obtaining the difference of the differential delays, $\frac{1}{2}[(\tau_1^{TX} - \tau_1^{RX}) - (\tau_2^{TX} - \tau_2^{RX})]$ is straightforward. The calibration station has to be collocated with stations 1 and 2 and two-way time transfer measurements using a common clock for both stations have to be carried out between the calibration station and the respective on-site station. Applying (1) and designating the calibration station as station 3 for a zero clock difference—under the assumption of reciprocity—the differences of the equipment delays for the two pairs of stations are given by:

$$\frac{1}{2}\left[\left(\tau_1^{TX} - \tau_1^{RX}\right) - \left(\tau_3^{TX} - \tau_3^{RX}\right)\right] = \frac{1}{2}\left(\Delta T_3^1 - \Delta T_1\right) \tag{2}$$

$$\frac{1}{2}\left[\left(\tau_2^{TX} - \tau_2^{RX}\right) - \left(\tau_3^{TX} - \tau_3^{RX}\right)\right] = \frac{1}{2}\left(\Delta T_3^2 - \Delta T_2\right) \tag{3}$$

with ΔT_3^1 and ΔT_3^2 the counter readings obtained with station 3 at sites 1 and 2, respectively. The wanted quantity, the difference of the equipment delays of stations 1 and 2, is obtained by subtracting (3) from (2):

$$\frac{1}{2}\left[\left(\tau_1^{TX} - \tau_1^{RX}\right) - \left(\tau_2^{TX} - \tau_2^{RX}\right)\right] = \frac{1}{2}\left(\Delta T_3^1 - \Delta T_1\right) - \frac{1}{2}\left(\Delta T_3^2 - \Delta T_2\right). \tag{4}$$

The terms at the right hand side of (4) are known from the measurements carried out at both sites.

III. Implementation

A. PN-Modems

Spread spectrum (SS) is a modulation technique where—in contrast to other band spreading modulation schemes such as frequency modulation (FM)—not the information-bearing function itself, but another function is used for spreading the bandwidth and where the expansion of the bandwidth is well beyond what is required to transmit the data. Though being more complex than classical modulation methods, SS-systems have many interesting and also unique features which make them most effective

for specific applications such as high resolution range measurements and high precision and accuracy time transfer [17], [18].

For ranging and timing applications the so-called direct-sequence or pseudonoise (PN) technique is used [17], [18], [25], [46]. Here, the spreading is achieved by multiplication of the data by a binary pseudo-random sequence (PN-sequence) whose clock rate (chip-rate) is higher by several orders of magnitude than the binary data rate (bit-rate). In most cases, binary phase shift keying (BPSK) is used for the modulation of the carrier. The transmitted signal is indistinguishable from the normal communications link noise except from an increase in the noise density over the occupied bandwidth. At the receiving site, the signal is despread by multiplication with a locally generated replica of the code, thereby spreading interfering signals and thus improving the signal-to-noise ratio. The improvement obtained is the so-called processing gain. For the necessary correlation of the codes, the locally generated code has to be shifted until both codes match. For ranging and timing applications the crucial information is the delay between the transmitted and received codes. This delay is measured via the amount by which the locally generated code has to be shifted in order to correlate with the received one. If the time delay to be measured is longer than the code sequence the resulting ambiguity has to be resolved by the transmission of additional information. The resolution of a ranging or time transfer system employing PN-sequences depends on the duration of a code element, the chip-length, but the shorter the chip-length the higher is its reciprocal value, the chip-rate and therefore the bandwidth needed. Long PN-sequences yield better interference suppression but need a longer time for code synchronization. Thus a compromise has to be found according to the specific application. By the use of orthogonal codes (low cross-correlation), several such codes can be transmitted simultaneously in the same frequency band of a satellite transponder without interfering with one another. Such a multiple access scheme is called code division multiple access (CDMA) [7], [46] and is most important for the reciprocity issue of the two-way time transfer (see term three at the right hand side of (1)).

Although PN-signals were already used twenty years ago for two-way time transfer within the Defence Satellite Communication System (DSCS) [47] and even earlier for ranging applications [48] the first commercial available PN-modem was the microwave time and ranging experiment (MITREX)-modem. It was developed by Professor Hartl in Germany, about ten years ago for time transfer of highest precision and accuracy using geostationary satellites and for the purpose of ranging to these satellites [25]. The modem, also known as Hartl-modem, transforms the 1 pps of the local clock into a binary sequence with a chip-rate of 2.5 MHz and a length of 4 ms and it provides up to 8 orthogonal codes, thus allowing it to be used in a CDMA system. The modulation scheme used is BPSK and according to the chip-rate of 2.5 MHz to transmit the signal a bandwidth of 5 MHz is sufficient, but may be further reduced by appropriate filtering. The modem uses a fixed intermediate frequency of 70 MHz whereby the center frequency of the received signal is only allowed to deviate by some kilohertz from the nominal 70 MHz for delay variations smaller than 0.5 ns [28]. A new microprocessor controlled digital version of the modem will have a high resolution counter as integral part of the modem and will provide some more advanced features [49]. The signal delay of the modem is practically constant for a wide range of the operational parameters, and for a carrier-to-noise density ratio (C/N_o), a figure describing the quality of a satellite link [7], [50], above 55 dBHz the typical measurement precision is better than 1 ns with a limit of about 0.1 ns.

In the near future an additional PN-modem developed in the United States at the Naval Research Laboratory (NRL), Washington, DC, will be commercially available [51], [52]. It will be of a flexible all-digital design allowing a variety of different codes to be employed thus providing compatibility with existing equipment such as the MITREX-modem. It will also provide frequency agility and the capability to transmit the measurement data over the same satellite link simultaneous with the time transfer operation.

NIST also is developing a PN-modem for time transfer experiments using geostationary satellites.

B. Space Segment

Satellite transponders suitable for two-way time transfer are available worldwide on International Telecommunications Satellite Organization (INTELSAT) satellites and on European Telecommunications Satellite Organization (EUTELSAT) satellites in Europe as well as on various domestic and experimental satellites; making use of certain frequency bands dependent on the satellite system and the service region. It is therefore possible to use different space segments for satellite time comparisons. For intercontinental satellite time transfer, INTELSAT satellites are of special interest because they provide worldwide coverage, but one has to also consider satellite capacity offered by private companies such as Pan American Satellite (PANAMSAT) and by INTERSPUTNIK, the eastern counterpart to INTELSAT.

INTELSAT is a cooperative of 119 member nations that owns and operates the global commercial communications satellite system. The access to the INTELSAT space segment is controlled by the respective national entities. These entities are responsible for the operation of earth stations accessing INTELSAT satellites. The earth stations may be owned by the entities, by common carriers, or by the end users, depending on national policy. Thus prospective users have to arrange with their national entities for earth station operation and for the right to use the INTELSAT space segment [53], [54]. INTELSAT operates satellites serving the Atlantic ocean region (AOR), the Indian ocean region (IOR), and the Pacific ocean region (POR). In [53] and [54] one can also find details about the possible connections by C-band and Ku-band links via these satellites and the frequencies employed as well as information about the different services offered by INTELSAT for digital links between small earth stations. Furthermore, link budgets

are given for C-band and Ku-band links between North America and Europe using the satellite at 307° E under the assumption of the use of Ku-band and C-band antennas with a diameter of 1.8 m (VSAT's) and 4.5 m, respectively, and the transmit power set to produce a C/N_o of at least 54 dBHz. This C/N_o, suitable for MITREX operation, can be obtained with transmitting powers of about 1 W. These levels are substantially smaller than those needed in previous experiments where conventional modulation schemes had been employed.

In order to find the carrier-to-noise density (C/N_o) by means of link budget calculations, one needs the equivalent isotropically radiated power (EIRP) of the transmit station which results from its antenna gain and output-power of the power amplifier, the satellite transponder characteristics, and the figure-of-merit (G/T) of the receive station, resulting from its antenna gain and system noise temperature. The transponder is characterized by the power flux density needed for its saturation, the corresponding EIRP, and the transfer characteristics (input and output backoff) of its output amplifier [50].

C. Satellite Earth Stations

When intending to set up an earth station, one has first to contact the national entity responsible for the operation of satellite links in order to get informed on the procedures and modalities. The next step is to define the station parameters from link budget calculations, which is best done in close cooperation of the end user, the national entity, and the organization operating the space segment which shall be used. The crucial parameter in this calculation is the C/N_o, necessary for proper operation of the PN-modem to be used. In order to get the earth station approved, of course it has to comply with the technical and operational requirements stated by the organization operating the space segment. Using satellites operating at Ku-band frequencies, the MITREX-modem can be used with earth stations employing antennas of 1.8 m in diameter, state-of-the-art LNA's and SSPA's of a few watts or even less, and providing an IF of 70 MHz.

There are two possible approaches for the earth station design [55]. First a rather expensive but most flexible one which can be used for all Ku-band up link and down link frequency bands, employing independent synthesizers in the up and downconverters and with synthesizer step sizes small enough to comply with all requirements of different satellite services. Second the inexpensive, but also inflexible approach of using a VSAT (see Fig. 2). Most VSAT's use a common synthesizer for the up and downconverter, and are therefore laid out for a certain satellite translation frequency and generally provide only 1 MHz synthesizer step size [15], [29], [31], [55]. This is no problem when they are used with modems providing the necessary frequency agility to use any allocated frequency and to compensate for deviations of the satellite translation frequency from its nominal value. The next generation of PN-modems for time transfer will offer this flexibility [49], [51], [52]. For the use of the original MITREX together with a VSAT,

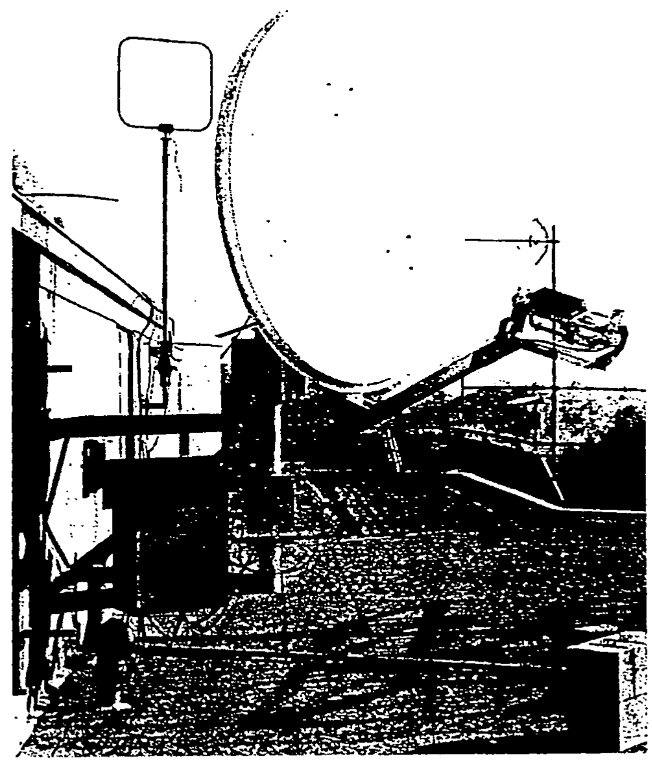

Fig. 2. VSAT (1.8 m dish) installation. The RF equipment with its power supply is attached to the mount and the LNC and SSPA are mounted directly behind the feed.

one has to either modify the VSAT in order to get the needed frequency agility or to be restricted in its use to certain satellite services and to using it together with a fully frequency agile partner station [29], [31], [55].

D. Calibration

In order to make use of the inherent high accuracy time transfer potential of the two-way method, one has to either determine the differences of the differential delays of the stations involved or the differential delay of each station separately. The theory of the first method is given in detail earlier in this paper. It can be implemented by the use of mobile stations or transportable small flexible stations so-called fly-away terminals with collapsible antennas as used for news-gathering at remote places [34], [56]. An important issue of course is the delay stability of the calibration station itself.

A second method makes use of a kind of satellite transponder attached to the stations which allows one to measure the round trip delay of the station including the antenna, and the transmit delay alone, thus allowing to compute the needed differential delay of a station [45]. An important aspect of this method is the possibility to check the delays frequently.

IV. Existing Links And Results

Operational links exist in North America between NIST and USNO and NIST and NRC (National Research Coun-

cil), Ottawa [12], [33], [34], [57], and in Europe there exists an experimental link between OCA (Observatoire de la Côte d'Azur), Grasse, and TUG (Technical University Graz), Graz, supporting the LASSO experiment [58]-[60]. The time transfer between NIST and USNO makes use of a leased Ku-band channel on a domestic satellite and the European link employes an EUTELSAT channel also operating at Ku-band frequencies.

Measurements have been carried out at NIST and USNO since 1988 three times per week. Each session consists of measurement periods of 300 s duration during which second-to-second measurements are done simultaneously at NIST and USNO [33], [34]. The standard deviation with respect to the mean—a measure of precision of the time transfer—of the second-to-second differences varies between 0.2 ns and 1.5 ns for high C/N_o and low C/N_o, respectively (an example is given in Fig. 3). The results obtained show that the measurement time could be reduced from 300 s to 100 s with little or no compromise in precision even with a C/N_o as low as 55 dBHz [33]. In-cabinet and free-space loop-around tests by means of a satellite simulator were carried out in order to determine the stability $\sigma_y(\tau)$, the square root of the Allan variance [61], of the two-way satellite equipment used [29], [31]. For a C/N_o of 55 dBHz a $\sigma_y(\tau)$ level of $2 \times 10^{-9}\tau^{-1}$ (τ in seconds) was obtained, but usually the USNO-NIST time transfers have a C/N_o better than this. These results are in good agreement with the OCA-TUG measurements (see Fig. 4).

In order to determine the accuracy of the method, equipment delay calibrations are necessary. Since 1989, such measurements are carried out by means of a mobile earth terminal [12], [56].

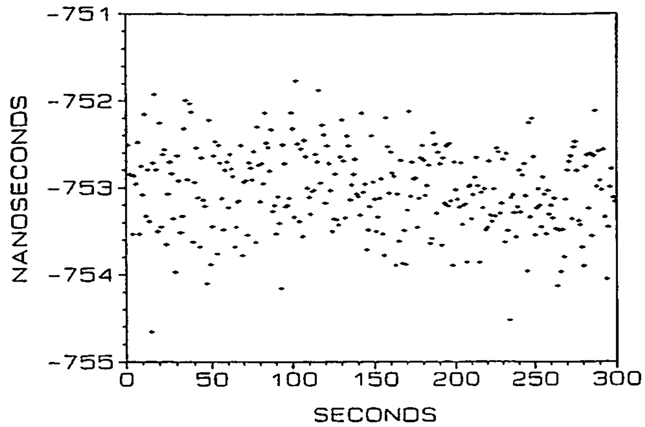

Fig. 3. Sample plot of uncalibrated USNO-NIST second-to-second time differences (standard deviation 482 ps) of 12-03-1990 starting at 15:30:00 UTC (data courtesy W. J. Klepczynski, USNO).

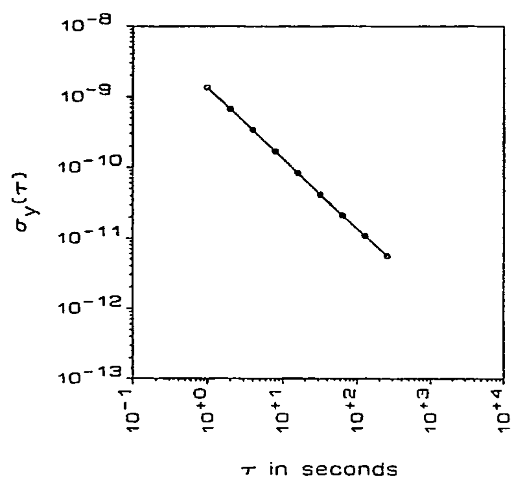

Fig. 4. Stability (square root of the Allan variance) of OCA-TUG measurements ($\sigma_y(\tau) = 1.3 \times 10^{-9}\tau^{-1}$).

V. Summary And Prospects

Since the very beginning of satellite communications two-way time transfer measurements have been carried out. The great advantage compared with one-way measurements is that one does not need the positions of the stations and the actual satellite position with high accuracy. The disadvantage is that the stations also have to transmit. Over decades generally dedicated telecommunications earth stations had to be used; a fact which caused several problems and in most cases degraded the performance because of the need of terrestrial links between the timekeeping institutions and the earth stations. The rapid development of satellite technology and the commercial availability of spread spectrum modems now makes it possible to use small and inexpensive on-site earth stations. Several experiments have been carried out making use of these developments and for about two years now an operational link between NIST and USNO using a domestic communication satellite has been in place. The precisions achieved are in the subnanosecond range and one expects accuracies of at least one nanosecond using small transportable stations for delay calibration.

Due to the available precision and its high accuracy capability and the fact that it is a pure civilian system, the two-way time transfer via communication satellites will become the preferred choice for future operational systems demanding the utmost performance. In addition to the activities in North America, there are plans to establish two-way links between major time keeping laboratories in Europe. Similar activities exist in the Asian region; notably, Japan was very active in this field from the very beginning. Within these regional networks the combination of one-way and two-way methods using the same spacecraft would be of special interest in providing a means of precise satellite position determination for one-way users [19].

The future scenario of high precision and high accuracy time transfer will probably consist of two-way networks in certain regions as Europe, Asia, and North America and some intercontinental links to connect these regions. For these intercontinental links, the INTELSAT space segment or satellite capacity offered by other organizations or private operators will be used. The plans for the European and North American link using the INTELSAT satellite at 307°E are close to its realization. There are also plans for a link between Japan and Europe. The necessary periodical

calibrations shall be done by the use of mo[illegible]tations and fly-away terminals.

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